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A system and stakeholder approach for the identification of condition information: a case study for the Swedish railway

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Abstract: The purpose of this paper is to identify stakeholders' need for system condition information in order to improve railway punctuality. The paper provides a holistic formulation of maintenance-related punctuality problems within the interface between the contact wire and the pantograph. From the identified problem formulation, the information needed to support the maintenance of technical functions can be identified. The incorporated system and stakeholder perspective adds a dimension to the explanation of what information is needed and why it is needed. The system and stakeholder perspective on the assessment of the information need can serve as decision support when acquiring new condition monitoring technologies. On the basis of the problem formulation, this perspective can also serve as an illustration of how information is to be used to improve punctuality. In order to identify stakeholders' need for system condition information, a failure mode and effects analysis (FMEA) approach was used. The FMEA is complemented with information derived from informal interviews performed with a variety of experts working with issues related to contact wires and pantographs. The applied methodology can be useful for conducting further research studies on other stakeholder and engineering interfaces, such as the wheel–rail interface.

Keywords: maintenance, information, system, stakeholder, railway, contact wire, pantograph

1 INTRODUCTION

The Swedish railway sector is partly deregulated, which means that private entities are allowed to compete for contracts to perform infrastructure maintenance on the rail network. This also applies to rolling stock operation, where private entities are allowed to perform traffic operation on the rail network. In Sweden, 80 per cent of the railway network is owned by the Swedish Government [**1**]. The Government controls the infrastructure and most of the Swedish railway sector through Banverket (the Swedish Rail Administration). Banverket's main objectives, stated in the governmental transport policy objectives, are to ensure system safety, cost-effectiveness, reliability of service, and sustainability, for example in terms of environmental impact and longevity of transportation provision for the public and industry. Governmental requirements state that Banverket has a sector responsibility for the railway, which means that it has an overall responsibility for the whole railway. This implies that Banverket should monitor and actively pursue development throughout the whole railway sector [**1**]. Hence, the responsibility for improving punctuality, among other things, lies with Banverket [**2**]. This government agency can affect the behaviour of stakeholders (operators and infrastructure maintenance contractors) within the railway sector by creating regulations or constructing contracts, of which some have economic incentives attached [**2**].

Being responsible for the overall functioning of the transportation system, Banverket must also monitor the behaviour of stakeholders who affect the functions of the system. Infrastructure maintenance contractors are responsible for the functions of the infrastructure, and the traffic operators are responsible for the functions of the rolling stock. Therefore, it is important to consider what kind of information infrastructure maintenance contractors and operators need, respectively, in order to control the condition and degradation of their respective subsystem functions. It is also important to consider what kind of information Banverket needs in order to objectively assess the effectiveness (doing the right things) and the efficiency (doing the things right) of the maintenance work performed by the various stakeholders.

Banverket has initiated studies to explore how the punctuality of the railway system can be improved by applications of condition monitoring technologies [**3**]. To execute condition-based maintenance successfully, it is necessary to have control of both the technical health and the degradation behaviour of items [**4**, **5**]. One of the main purposes of using condition monitoring technologies is to allow system health information to serve as decision support for effective and efficient maintenance management. At present there are numerous different technologies available for monitoring the condition of railway systems [**6**–**8**]. There is definitely no shortage of initiatives from industry to provide condition monitoring solutions to solve maintenance-related problems. Hence, finding a possible solution to the task of obtaining health information about the functions of technical systems is unlikely to be a major problem. The problem may be more related to finding a proper solution. A proper solution does not necessarily focus on what can be measured, but rather on the kind of information needed. This can be illustrated by problems related to low testability and insufficient integration of different maintenance echelons, e.g. no-fault-found (NFF) events [**9**, **10**]. A proper solution is rather a solution that can provide the decision support required for effective and efficient maintenance management. From such a perspective, there arises a need for critical assessment of the technology itself and, primarily, the characteristics of the problem that is to be solved.

The maintenance-related punctuality problem that is under scrutiny in this paper concerns the contact wire–pantograph system interface. A holistic problem formulation for the system is established to identify information that is relevant to controlling the technical health and degradation of the system. Moreover, the problem formulation is relevant to understanding why the information is needed. The aim of the study is therefore to use the problem formulation as a guideline for identification of the need for information from both a system and a stakeholder perspective. It is important to ascertain what information Banverket, the infrastructure maintenance contractors, and the traffic operators need to fulfil their respective responsibilities and to understand why that information is needed. This can act as input data that can help identify what kind of condition monitoring solutions can provide the decision support required for effective and efficient maintenance management. It can also help to illustrate how the same information is useful from different stakeholder perspectives (which is worth considering when acquiring condition monitoring solutions), as well as helping to estimate the improvement potential of applying condition monitoring solutions.

The contribution of this paper, in addition to the attempt to construct a holistic problem formulation of the contact wire–pantograph interface and to apply the stakeholder perspective to the information needed, is the exploration of the methodology used within the study. This methodology may perhaps be applicable to the rail–wheel interface or, for that matter, to other interaction-dependent engineering systems.

The outline of the remaining part of this paper is as follows. In section 2, the studied contact wire–pantograph system and its stakeholders are introduced. In section 3, the research approach applied is presented and justified. Section 4 contains the analysis and results of the performed study. This section is first divided into subsections dealing with the contact wire and pantograph subsystems, respectively, and then into subsections treating the modes, causes, and effects of failures. In addition, the currently applied condition monitoring methods and the perspectives of the stakeholders are presented, with an emphasis on related information requirements. Section 5 contains a discussion about the results of the study, and section 6 gives some concluding remarks.

2 THE STUDIED SYSTEM AND ITS STAKEHOLDERS

Electric energy for the Swedish railways is supplied at high voltage to feeder substations, where the voltage is reduced to a suitable level (15 kV 16.7 Hz) and fed to the railway contact wire system to be used by locomotives

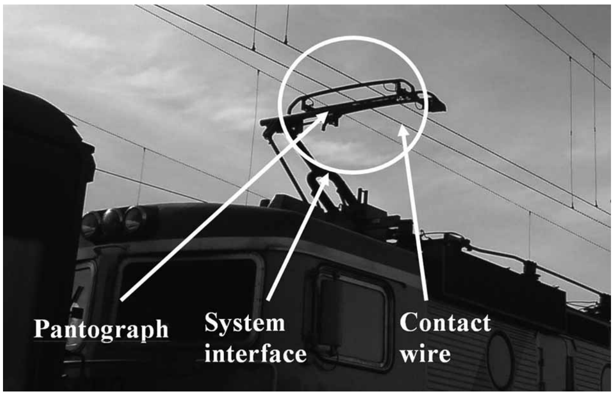

Fig. 1 The contact wire, the pantograph, and their critical system interface

and trains. On railways, the electric current passes from the contact wire via the rolling stock's pantograph to the locomotive (Fig. 1), where the energy is used by electric motors and fed to the earthed rails, which are part of the return circuit. Hence, the overall purpose of the contact wire–pantograph system is to transfer electric energy properly from the infrastructure to the rolling stock. Therefore, certain behavioural characteristics of both the infrastructure and the rolling stock must be guaranteed in order to achieve this overall purpose. In other words, certain demands on specific functions of both the infrastructure and the rolling stock must be met in order to achieve a proper transfer of electric energy.

Table 1 illustrates the top five reasons for infrastructure-related train delays in Sweden during 2004–06 (these figures are approximately the same every year).

Contact wire and track failures take turns at being the dominant infrastructure subsystems causing the most train delay time. Contact wire failures happen less often than turnout failures, but when they do occur, they tend to block traffic for quite some time (6.2 h on average, Table 1). Turnouts contribute the most train delays, but the average delay per fault for turnouts is quite low (0.9 h on average) compared with that for the contact wire. One interesting observation is the number of train delays attributed to each asset. If assumed that the time that it takes from the system fault recognition to the initiation of a corrective maintenance action is similar for both the contact wire and the turnout, this would imply that the time impact from the maintenance identification to the maintenance initiation is six times greater for turnouts than for the contact wire. However, contact wire still causes the most train delay time, so it can be concluded that contact wire faults are far more critical than turnout faults.

When large traffic disruptions occur, Banverket starts cancelling trains in order to reduce knock-on delays (trains that are delayed due to other delayed trains) on the network. Cancelled trains are not reported in any delay statistics. Hence, the total effect of large traffic disruptions will never be apparent in the delay statistics. Therefore, the influence on train delays from failures on track or contact wires is underestimated to a higher degree in the delay statistics than the corresponding influence from other subsystem failures. Banverket has no exact time limit for deciding when to start cancelling trains. This is instead determined by the traffic controllers on a case-to-case basis. Nor is there any correlation made between the number of cancelled trains and the causes of delays, so it is impossible to estimate exactly how many trains are cancelled due to each subsystem failure, respectively.

In order that the infrastructure maintenance contractors may forecast effectively the need for preventive maintenance, the contractors depend on the deterioration caused to the infrastructure by the rolling stock being as predictable as possible, and small enough to enable adequate response time. However, the train operators adopt a similar strategy when focusing on their rolling stock. The interrelationship between the stakeholder roles and the physical interaction of their assets (through the wheel–rail and pantograph–contact wire interfaces) is complex, since it is difficult to pinpoint the causes of failure interactions within the interfaces. Related examples can be found throughout the railway sector, where the increased strength of rail causes reduced serviceability of wheels or where the increased hardness of wheels causes reduced serviceability of rail [**11**, **12**].

Fig. 2 is an illustration of train delays related to the top 30 reported causes of contact wire failure.

According to failure statistics (Fig. 2), failures of the rolling stock's pantograph are responsible for ~20 per cent of the contact wire-related train delays. The real delay contribution from pantograph failure is (according to Banverket experts) estimated to be somewhere ~40 per cent. This is, however, not visible in the statistics, being hidden behind causes such as train vehicle, unexpected mechanical stress, fatigue of material, and cause not registered, which also contain an influence from pantograph failures.

Table 1 Top five causes of infrastructure-related train delays, 2004–06

No.	Subsystem Years 2004–06	Delay attributed to infrastructure (%)	Delay attributed to infrastructure (h)	Number of train delays	Average delay attributed to each failure (h)
1	Track	20	7173	2995	2.4
2	Contact wire	18	6370	1030	6.2
3	Turnout	17	5963	6383	0.9
4	Signal box and section block	13	4764	3703	1.3
5	Positioning system	5	1808	2646	0.7

Data collected from Banverket's TFÖR (train-delay registration) system.

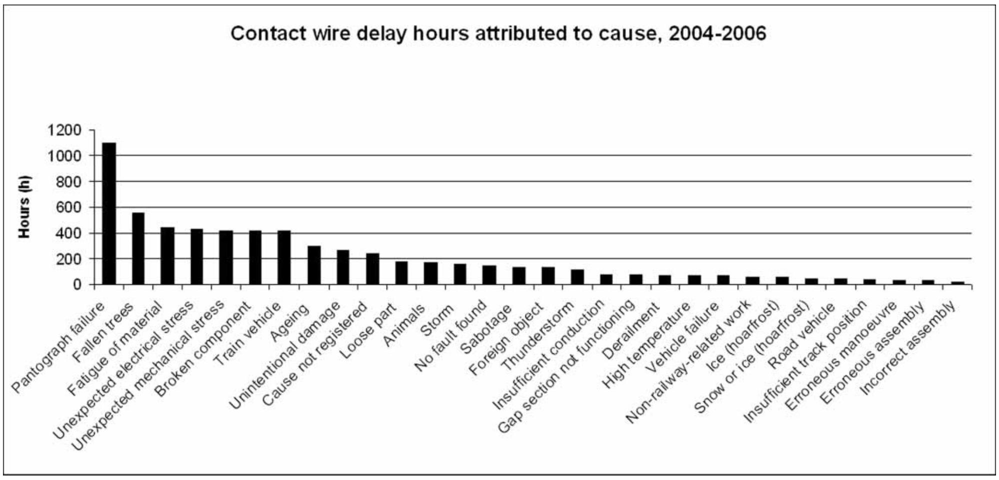

Fig. 2 Illustration of the top 30 causes of train delay time related to the contact wire system. Data collected from Banverket's failure/fault report system 0felia

3 APPROACH

As a first step to enforce punctuality improvement (given the responsibility bestowed on Banverket by the Swedish Government), a set of control indicators must be identified. These are indicators that assess whether the stakeholders (operators and contractors) manage to deliver adequate system functions (functions required to enable adequate train operation). Consequently, a focus of this paper is to identify what condition information is needed in order to monitor the health of the functions delivered by the maintenance effort of the respective stakeholders. To highlight the necessity of acquiring knowledge of the subsystem conditions, the paper also focuses on describing why information is needed from different stakeholder perspectives.

A fault is in this paper considered at the system level, and, therefore, a train delay is a fault. A failure is regarded as a subsystem function that has deviated from its prescribed performance criterion, but has not yet caused a system fault.

The systems' functions and interactions are explored using qualitative data analysis [**13**]. The failure mode and effects analysis (FMEA) methodology [**4**, **14**, **15**] is used to explore the problem inductively from the component level via the subsystem failure mode to the system level fault. This approach is chosen due to the study's focus on inductively exploring functions and information for failure mode identification and failure mode localization [**4**, **5**, **16**], concerning the contact wire–pantograph system, rather than on deductively studying them through, e.g., fault tree analyses (FTAs) [**17**].

The FMEA relating to the contact wire and the pantograph functions contained (according to the guidelines in IEC 60812) an expert assessment of what kind of subsystem functions the respective systems are to deliver (to assure a proper power conduction), the possible causes of absence of function, the local effect (of absence of function), the end-item effect (train delay), the applied methods for detection of failure, the present fault-prevention provisions, and, finally, the information needed to control the health of each identified function, respectively.

Some delimitations were used in the FMEA study. The study does not regard the functions of the power supply to the contact wire system. The pantograph functions that are considered are only those functions whose absence can cause damage to the contact wire. It was also assumed that the systems are not expected to perform beyond what they are designed to do. In other words, it is assumed that proper maintenance is sufficient to assure a proper system function. Consequently, design changes to cope with deviating performance requirements were not dealt with to any extent. Moreover, only functions whose absence could propagate into a system fault (train delay) were considered, i.e. the end-item effect is the same for all the identified failure modes.

Even though the study was not conducted as a failure mode, effect and criticality analysis (FMECA), some effort was made to retrieve a priority ranking of the identified failure modes and to assess the detectability of the failure modes by the currently applied condition monitoring methods. FMECA is an extension of FMEA to include a criticality assessment of the failure modes and thereby allows a prioritization of countermeasures [**15**]. The two major criticality assessment approaches that are normally utilized in FMECA applications are based on the criticality matrix or the risk priority number (RPN) [**15**]. However, in some cases, the necessary information is not available and it becomes necessary to revert to a simpler form of a non-numeric FMEA [**14**, **15**, **18**]. In this study, no relevant historical data are available. Hence, no analytical methodologies, such as FTA and event tree analysis, or simulations could be used to estimate the frequencies of unwanted events [**19**]. However, for the purpose of the present FMEA, it is believed that expert judgement is sufficient and that a Delphi-influenced approach [**20**] is appropriate to elicit the experts' estimates of failure mode prioritization and the failure modes' degree of detectability. Regarding the priority ranking estimation, it is believed that a criticality matrix approach (considering a combined estimate of severity and probability) is sufficient to render a priority ranking of failure modes (see e.g. IEC.60300-3-9 [**19**]), especially when considering the inconsistency of RPN (see Kmenta and Ishii [**18**] for a thorough discussion about the limitations of RPN). To extend the performed FMEA by further pursuing the estimation of the severity and of the probability of identified failure modes, a more formal FMECA could be applicable. This could be carried out by applying the analytic hierarchy process or some other methodology for pair-wise comparison, as described by Saaty [**21**]. Another possibility would be to apply the expected cost approach in a scenario-based FMEA, as presented by Kmenta and Ishii [**18**].

The study was conducted in four parts. The first part of the study was a deductive exploration of contact wire failures and train delay statistics, much of which has already been presented in section 1. This part of the study was performed to obtain an initial problem formulation for the forthcoming parts of the study. The second part of the study was the FMEA effort, which was performed at Banverket's headquarters. The FMEA study was conducted in cooperation with three contact wire experts with several years of experience of working with contact wire systems. The FMEA study formulated the baseline problem description for the contact wire–pantograph system.

In order to include the stakeholders' perspectives, the third part of the study involved informal interviews with infrastructure managers, infrastructure maintenance contractors, traffic operators, pantograph experts, rolling stock workshop staff, and personnel operating Banverket's measuring wagon (STRIX). Some of the interviewees (pantograph experts and traffic operators) were identified during an annual pantograph expert meeting at Banverket's headquarters (which the author attended). Other interviewees were selected based on the recommendations from Banverket and the traffic operators (infrastructure managers, maintenance contractors, rolling stock workshop staff, and STRIX personnel). During these interviews, the interviewees had the chance to reflect on the results from the FMEA problem formulation created by the Banverket experts. The interviewees were also requested to declare how present maintenance practices were conducted. Additional information from the interviewees was incorporated into the study. The fourth part of the study is an analysis of the information retrieved, which is presented below.

4 ANALYSIS AND RESULTS

To provide a structured description of the complex problem connected with the contact wire–pantograph interface, this section is divided into two parts. The first part (section 4.1) provides a system perspective by giving a description of contact wire and pantograph failure modes and the methods that are applied to monitor these failure modes. This section gives a perception of what kind of information is needed to gain control of the failure modes. The second part (section 4.2) adds the stakeholders' perspective on the problem (described in section 4.1) to illustrate why the information is needed.

4.1 System perspective

This section first provides a description of contact wire failure modes and the methods that are applied to monitoring these. Subsequently, the pantograph is dealt with in a similar manner. Finally, a priority ranking of the identified failure modes is presented, together with an assessment of the failure modes' degree of detectability using the applied condition monitoring methods.

4.1.1 Contact wire failure modes, effects, and causes

The identified contact wire failure causes and failure modes, the local effects, the end-item effects, and how they are inter-related are illustrated by the causal map in Fig. 3. The descriptions of the failure modes (FM), failure effects (FE), and possible failure causes (FC) are subsequently presented.

FM (horizontal displacement from the working point): The contact wire must stay within the prescribed horizontal distances from the centre of the track. This is necessary to avoid the contact wire reaching beyond the span of the pantograph's carbon slipper. The contact wire position must still fluctuate in relation to the centre of the track in order to enable an even degradation of the pantograph's carbon slipper. FE: If the contact wire position is out of tolerance, this can cause damage to the pantograph and, in a worst-case scenario, immediate dewirement (when the pantograph mounts the contact wire and tears it down). There is also a risk of insufficient power conduction (which can cause sparks and luminous arcs and damage both the contact wire and the pantograph). FC: Possible causes of loss of function are:

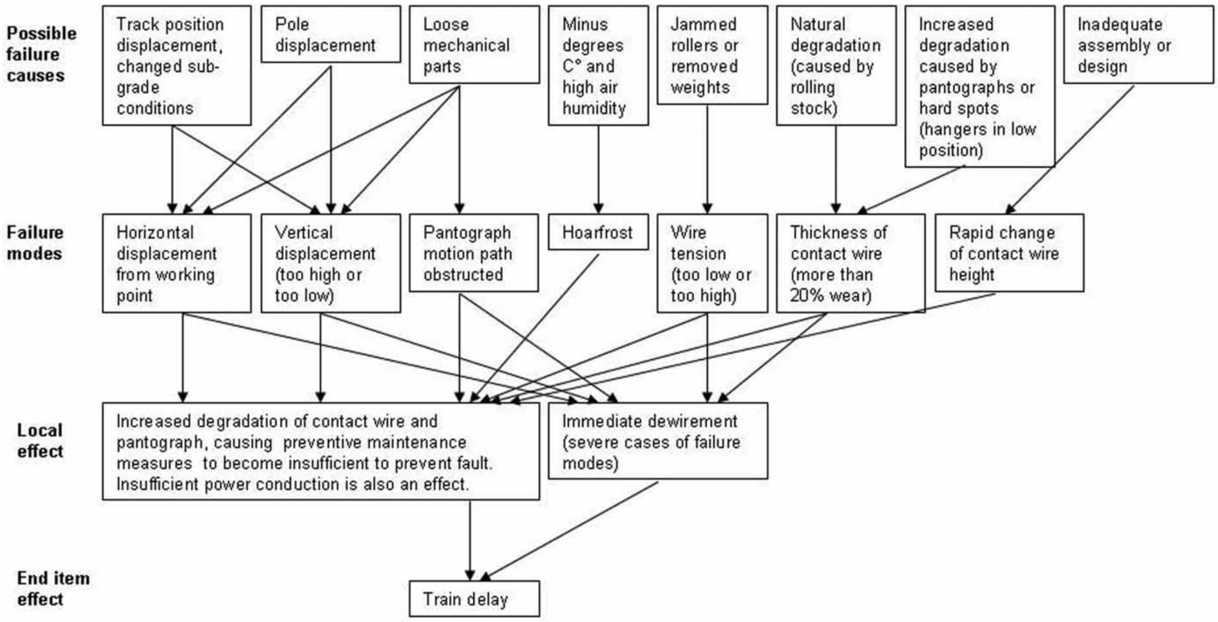

Fig. 3 Causal map of identified contact wire failure causes and failure modes, the local effects, the end-item effects, and how they are inter-related

displacement of the poles holding the contact wire; damage to or loosening of mechanical parts; or a change in the track position. One usual cause of displacement of the contact wire is non-coordination between contact wire adjustment actions and tamping actions performed on the track. Thus, the track position is changed, but the contact wire position is not adjusted accordingly.

FM (vertical displacement from the working point): The contact wire must stay below the prescribed highest vertical distances from the top of the rail. It must also stay above the prescribed lowest vertical distances from the top of the rail. FE: If the vertical position is too high, the pantograph cannot reach the contact wire. This causes a luminous arch, which can cause burn damages to the pantograph (damaging the carbon slipper and the glue holding it to the aluminium profile) and the contact wire or, in a worst-case scenario, immediate dewirement. If the vertical position is too low, there is a risk of damage to the pantograph's carbon slipper, immediate dewirement, and/or luminous arcs being discharged towards vehicles and cargo (which can be damaging to both the contact wire and the rest of the rolling stock). FC: Possible causes of high vertical displacement can be either pole displacement or low rails due to changed subgrade conditions. Possible causes of low vertical displacement can be a high track position due to changed subgrade conditions, low wire tension, or loose mechanical parts.

FM (pantograph motion path obstructed): The motion path of the pantograph must be free from obstacles in the infrastructure. FE: If the motion path is not free from obstacles, the pantograph will smash to misplaced infrastructure objects, causing damage to both the pantograph and the infrastructure. Severe cases can lead to immediate dewirement. FC: Possible causes can be loose or misplaced mechanical parts.

FM (hoarfrost). FE: If hoarfrost appears on the contact wire, the power conduction will be negatively affected. Hoarfrost causes luminous arcs between the contact wire and the pantograph, thus causing heavy degradation of the pantograph. The contact wire will also degrade more quickly. FC: The cause of hoarfrost is below zero temperatures combined with high air humidity, and hoarfrost is especially common in the northern parts of Sweden during September to November.

FM (the contact wire tension is either too high or too low): The contact wire must have a certain tension to withstand the pressure from the pantograph properly, preventing the pantograph from smashing to infrastructure objects. The tension of the wire is determined by the permitted maximum train speed: the faster the trains the higher the tension. This is to prevent dynamic motions (which can damage the system) between the contact wire and the pantograph. Tension weights are attached to the contact wire to ensure the proper wire tension. FE: If the wire tension is too high, the contact wire may snap. If the tension is too low, the contact wire position will be too low in relation to the top of the rail, thus increasing the risk of luminous arcs at the cantilevers (holding the contact wire). This also increases the risk of dynamic behaviour and bad power conduction. FC: The cause of insufficient wire tension can be that the rollers from which the tension weights hang are jammed or that the weights have been removed.

FM (too thin a contact wire): The contact wire must not (according to specifications) be degraded by >20 per cent of its original dimensions if it is to withstand the forces that are applied to it. FE: If the wire thickness is too low, the wire is likely to snap. FC: Single-point wear could be caused by trains standing still or hard spots (hangers in a low position, causing accelerated motion of the pantograph, in turn causing increased degradation of the contact wire and the pantograph's carbon slipper). Increased degradation can also be caused by pantograph failure (a damaged carbon slipper, too high or too low a lift pressure, or incorrect dynamic motion).

FM (rapid change of the contact wire height): If the contact wire height changes too rapidly, it is likely to cause accelerated vertical motion of the pantograph. FE: Accelerated pantograph motion causes increased degradation of the contact wire and the pantograph's carbon slipper. FC: Inadequate design or assembly might be the cause.

The only identified compensating provision against faults is to equip trains with double pantographs, so that, if one gets damaged, the other one can be used. A compensating provision against the hoarfrost failure mode can be to use a thicker carbon slipper, which can lessen the effects of hoarfrost. Further, a method for removing hoarfrost is to use the first pantograph (not electrically connected) on the train as an ice scraper. This is a method that was used in the past, but is no longer permitted under Banverket regulations. However, according to the interviewed traffic operators, there are just as many luminous arcs formed at the third pantograph as at the first when there is hoarfrost and when triple-headed locomotives are being used to haul heavy cargo.

4.1.2 *Applied methods for contact wire failure mode identification*

The applied methods for the detection of contact wire failure and the information needed to gain control of the failure modes are presented in the causal map in Fig. 4. The additional information required to gain better control of the respective failure modes, compared with the present-day situation, is represented by the information gap.

STRIX is Banverket's measurement wagon. The STRIX pantograph is in physical contact with the contact wire and measures the horizontal and vertical displacement of the contact wire (by use of accelerometers and strain gauges). In this way, it also records the dynamic behaviour of the pantograph's contact with the contact wire. Therefore, the measurements are influenced by the behaviour of the STRIX pantograph. According to Banverket experts, the accuracy of STRIX measurements is questionable.

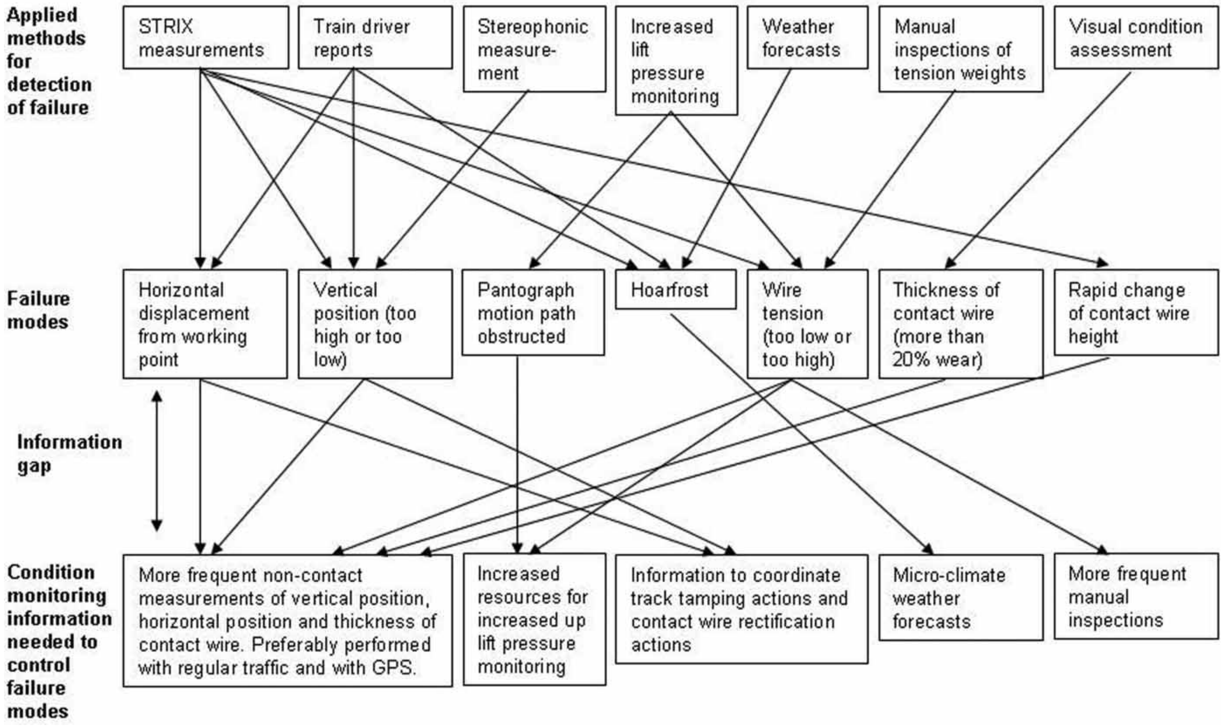

Fig. 4 Causal map of applied condition monitoring methods for detecting contact wire failure modes and the information needed to gain control of the failure modes

STRIX also takes video recordings of the infrastructure. However, these videos are rarely used for failure identification purposes. STRIX measurements are performed on most of Banverket's track structure (sidings at stations are excluded). STRIX is to perform at least two measurements per track section per year. The measurements are performed between March and November (the period from December to February being devoted to maintenance and upgrades of the system). It is interesting to observe that most of the problems relating to the contact wire and pantograph appear between November and March (when no measurements are made). Predetermined inspections and maintenance in the northern track region are performed on the contact wire system every third and sixth year (more rigorous inspection). In between these predetermined occasions, STRIX is the primary source of failure identification. If STRIX measurements indicate that the contact wire is out of tolerance, a work order is sent to the maintenance contractor to correct the problem. However, the contractor is frequently incapable of identifying the failure (i.e. NFF events occur) due to the inaccuracy of the kilometre positioning system used to localize the failure.

Figure 5 (a photograph taken at a train workshop) shows a sample of some 30 used pantographs, all of which show signs of degradation outside the tolerances of the carbon slipper (the new shiny pantograph being used as a reference). These pantographs all showed clear signs of burn damage caused by sparks or luminous arcs. The pantographs all indicate that the present maintenance practice is unable to keep the contact wire within acceptable horizontal and vertical distances. However, it should be noted that the contact wire will (according to Banverket experts) inevitably come into contact with the pantograph's aluminium profile when the trains come into or go out from sidings.

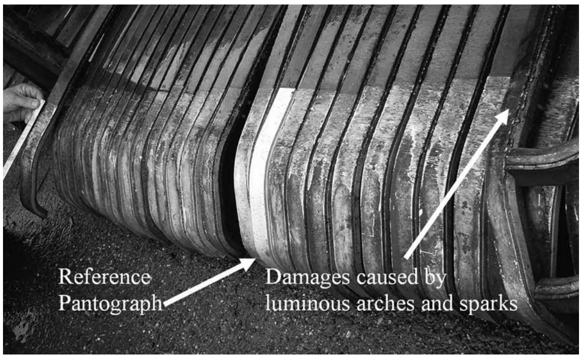

Fig. 5 Sample of some 30 pantographs showing signs of burn damage and degradation outside of the carbon slipper's work area

To achieve better control of the horizontal and vertical position of the contact wire, there is a need for more reliable and more frequent non-contact measurements of the vertical and horizontal position of the contact wire. This should preferably be performed with regular traffic and with the global positioning system (GPS).

Incorrect behaviour of the contact wire can be identified by the train driver, either as observations of contact wire motions, identification of sparks and luminous arcs, or as indications of bad power conduction from the train's line voltage metre. In some cases, the train driver reports identified and localized failures for the train traffic control centre. One way of identifying the positions of insufficient power conduction (where there are sparks and luminous arcs) is to merge GPS data with line voltage metre logs. With such information, the infrastructure maintenance contractor will be able to identify and localize failures that cause insufficient power conduction more accurately (low wire tension, hoarfrost, etc.).

Stereophonic measurements can be used to assess the distance between the rail and other infrastructure items; e.g. to assess whether the vertical position of the contact wire is too high or too low. However, these measurements are only used to assess whether cargo larger than the prescribed maximum sizes can be hauled without causing damage to the infrastructure. These measurements are used very occasionally.

Increased lift pressure monitoring is used to detect elements that can cause damage within the pantograph's motion path. This is not an automated method, since it involves lifting the contact wire to perform listening and visual inspections, filming and stopping to take pictures. There are only two measurement carriages in the whole of Sweden. The resources for these measurements are limited and, therefore, large proportions of the network are not monitored by this method. The interviewed traffic operators highlighted the importance of conducting these measurements in both directions, e.g. north and south, since their experience has shown that some failures only appear in one direction. It is important that the resources for this monitoring should be increased to gain acceptable control of the failure mode.

Weather forecasts can be used to predict hoarfrost. Micro-climate forecasts (local weather forecasts) can be one way of predicting the presence of hoarfrost even more accurately. However, their usefulness for the maintenance contractor can be questioned, since the trains will still be running. Of course, the forecasts can alert the contractor to necessary corrective maintenance activities, but the information is at present not of much use for preventive purposes. However, there are preventive methods that could be employed to remove or prevent the hoarfrost, which involve defrosting the contact wire (short-circuiting the wire and melting the frost) or treating the contact wire with glycerine. These methods are not applied today. The information could perhaps be of greater use to the traffic operators, who could (as they do during winter) shorten their carbon slipper inspection intervals. Micro-climate forecasts could perhaps be useful in a longer-term perspective. If the other failure modes are under control, the true effects of hoarfrost can be assessed, and, therefore, the information can be used as input data for the redesign of infrastructure and rolling stock components.

Tension weight rollers are lubricated at periodic intervals. The applied methods for inspecting the contact wire tension are STRIX measurements (STRIX being able to detect slack indicated as wire in a low position), increased uplift monitoring, and the manual lifting of counterweights to assure that the rollers are not jammed. Further resources are required to gain better control of this failure mode.

The thickness of the contact wire is occasionally inspected manually (visual inspection) by use of a cart running under the contact wire. However, this method is not especially accurate and very time-consuming. To gain control of this failure mode in an adequate way, it is essential to apply a non-contact condition monitoring method that at acceptable speed can localize the failures using GPS.

4.1.3 *Pantograph failure modes, effects, and causes*

The identified pantograph failure causes and failure modes, the local effects, the end-item effects and how they are inter-related are illustrated by the causal map in Fig. 6. The descriptions of the failure modes (FM), failure effects (FE), and possible failure causes (FC) are subsequently presented.

FM (lift pressure too high): The pantograph exerts a certain pressure towards the contact wire to assure proper power conduction, and the pressure is, in many cases, increased at higher train speeds. FE: If the lift pressure is too high, the pantograph's motion path can become obstructed (due to high operation). Besides increased degradation of the carbon slipper (due to high contact pressure), this can cause the pantograph to smash to infrastructure objects, thus causing dewirement. FC: One cause of too high an uplift pressure can be maladjustment of the pantograph.

FM (lift pressure too low). FE: If the lift pressure is too low, this can cause sparks and luminous arcs between the contact wire and the pantograph. In addition to increased degradation of the system, this also

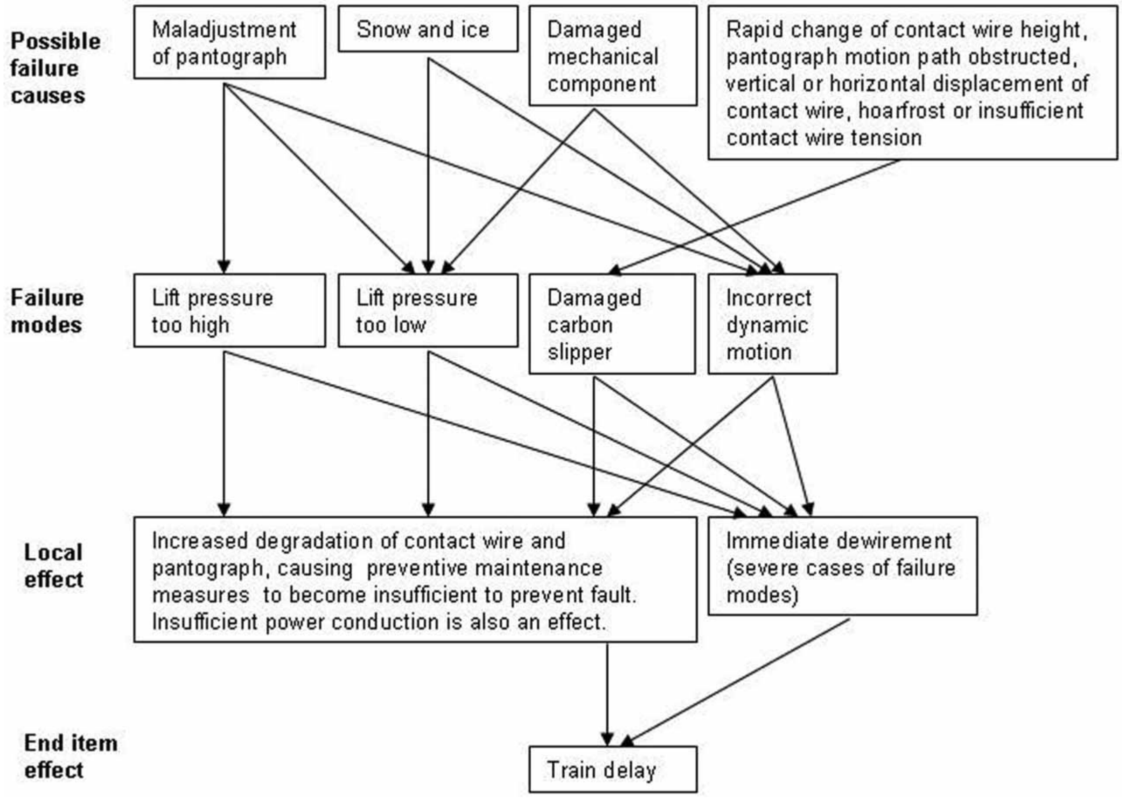

Fig. 6 Causal map of identified pantograph failure causes and failure modes, the local effects, the end-item effects, and how they are inter-related

causes bad power conduction. Severe cases can cause dewirement. FC: Too low a lift pressure may be caused by maladjustment of the pantograph, or snow and ice becoming attached to the pantograph and preventing it from operating properly.

FM (damaged carbon slipper): The carbon slipper is attached to the pantograph's aluminium profile. The function of the carbon slipper is to receive electric energy from the contact wire and at the same time allow for minimum degradation of the contact wire. FE: If the carbon slipper is damaged and pieces of carbon are removed, the aluminium profile will come into contact with the contact wire, causing increased degradation. Severe cases cause dewirement. FC: Possible causes of damaged carbon slippers are that the pantograph lift pressure may be too high or too low or that there may be incorrect dynamic motion of the pantograph. The following infrastructure failure modes can also cause damage: rapid change of the contact wire height; the pantograph's motion path being obstructed; vertical or horizontal displacement of the contact wire; and hoarfrost or insufficient contact wire tension. Another identified cause of carbon slipper failure is poor carbon quality [**22**].

FM (incorrect dynamic motion). FE: If the dynamic motion of the pantograph is incorrect, this can cause increased wear on both the contact wire and the pantograph due to the dynamic impacts and the luminous arcs that may appear. It may also be difficult to keep the pantograph's motion path free from obstacles (due to intensive operation). FC: The causes of incorrect dynamic motion can be maladjustment of the pantograph, ice or defective mechanical pantograph components, or insufficient contact wire tension.

The only identified compensating provision against the pantograph-related failure modes presented above is the automatic drop device (ADD), which is fitted on some locomotives. The ADD's primary function is to drop the pantograph when the carbon slipper gets damaged. There are also ADDs that drop the pantograph when too rapid vertical accelerations are applied to them.

4.1.4 *Applied methods for pantograph failure mode identification*

The applied methods for the detection of pantograph failure and the information needed to gain control of the failure modes are presented in the causal map in Fig. 7. The additional information required to gain better control of the respective failure modes, compared with the present-day situation, is represented by the information gap.

Too high a lift pressure can be monitored by the BUBO system, which measures the height of the uplift on the contact wire. The pressure measured is

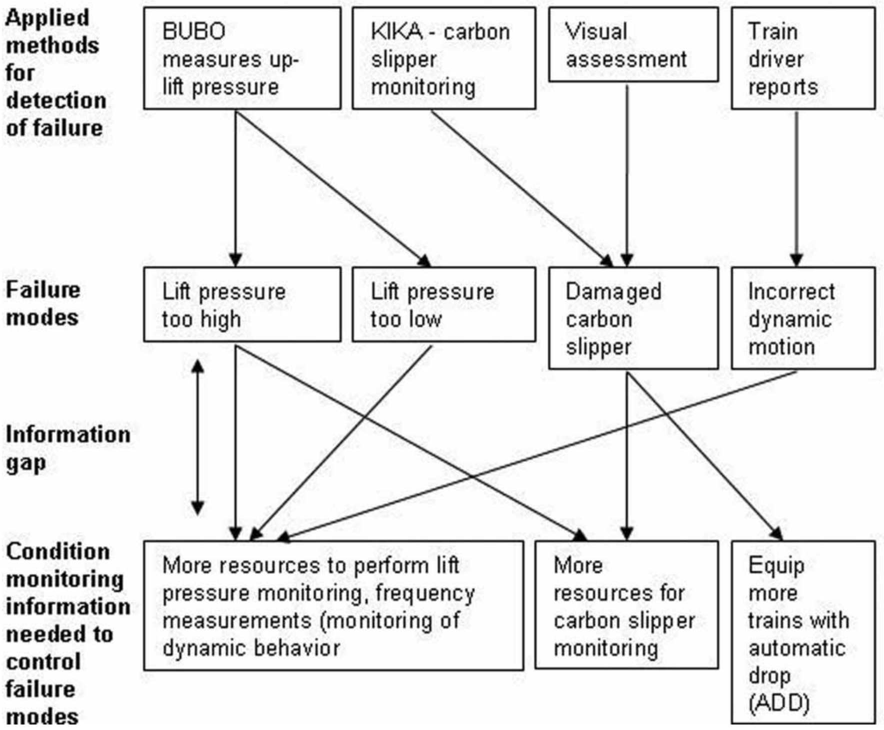

Fig. 7 Applied condition monitoring methods for detecting pantograph failure modes and the information needed to gain control of failure modes

based on the contact wire tension and the measured uplift. However, the measurement data from the current installation are questionable, since there has not been any calibration of the contact wire tension since the installation. BUBO can also monitor whether the uplift pressure is too low, but this function is not used at present. Hopefully, further developed uplift monitoring units will also be able to detect incorrect dynamic motions of the pantograph (frequency measurements). At present there is only one BUBO unit installed on Banverket's infrastructure. To gain control of this failure mode, there is a need for many more uplift monitoring units (calibrated units). Further, there is also a need to correlate the measurement data with vehicle identification information, preferably obtained by use of radio frequency identification (RFID) tags mounted on the rolling stock. Vehicle identification data can enable more reliable decision support (maintenance decisions based on more than one measurement and the possibility of trend detection).

The KIKA system is based on the same technology as that used in police speed cameras. KIKA uses radar to spot the presence of a pantograph, takes a picture of the pantograph, and performs an image analysis to determine the presence of pantograph failure. If a pantograph failure (e.g. a damaged carbon slipper or damaged aluminium profile) is spotted, an alarm sounds at the train traffic control centre, the train driver is contacted, and hopefully the pantograph is dropped. A few KIKA detectors are installed in Sweden, but their reliability differs. One problem is to get the camera to take a picture at the right moment as the pantograph passes. One way to make the function more reliable is to apply some form of radar-reflecting material on the pantographs and thus enable a more accurate positioning of the pantograph. The operators state that they are willing to attach such material if they can obtain access to the photos taken by KIKA (which, if connected to vehicle identification data, can be used for degradation assessment). As for uplift monitoring, there is a need for far more carbon slipper monitoring units and for better correlation to vehicle identification.

4.1.5 *Prioritization and detectability of identified failure modes*

In total, the FMEA resulted in the identification of seven infrastructure failure modes that must be controlled to enable the proper transfer of electric energy to the locomotives (Table 2). The study also identified four pantograph failure modes that must be controlled to receive electric energy from the infrastructure properly. The failure modes and the experts' judgements of the failure modes' priority and their detectability by using currently applied condition monitoring methods are presented in Table 2.

Table 2 Identified contact wire failure modes and pantograph failure modes, their estimated priority ranking, and estimated detectability

Priority	Failure modes	Detectability
Contact wire		
1	Pantograph motion path obstructed	2
2	Horizontal displacement from working point	5
3	Rapid change of contact wire height	2
4	Hoarfrost	3
5	Too thin contact wire	8
6	Vertical displacement from working point	3
7	Contact wire tension is either too high or too low	6
Pantograph		
1	Lift pressure too high	4
2	Damaged carbon slipper	3
3	Lift pressure too low	4
4	Incorrect dynamic motion	9

The priority ranking (1 = top priority) and the detectability judgements (1–10, where 1 is almost certain detection and 10 is almost impossible detection) in Table 2 can be used as indicators of which failure modes should receive attention first and for which failure modes applied condition monitoring practices are inadequate. Note that the detectability figure only represents the ability of the condition monitoring methods to detect the failure mode (while performing condition monitoring), not the overall detectability. For example, the increased uplift pressure monitoring method (Fig. 4) provides quite a good possibility of detecting the failure mode 'pantograph motion path obstructed' (Table 2). Hence, efforts to gain better control of this failure mode could be focused on increasing the frequency of this monitoring method. However, considering the failure mode 'horizontal displacement from working point', the applied monitoring methods seem inadequate. Hence, efforts to gain better control of this failure mode should initially be focused on finding and applying more appropriate monitoring methods.

4.2 Stakeholder perspective

Section 4.1 provided a perception of what kind of information is needed to gain control of the failure modes. This section adds the stakeholders' perspective to illustrate why the information is needed.

Independently of whether the initial failure mode is related to infrastructure or rolling stock, it is apparent that any one of the failure modes can inflict a loss of system function, causing delays and increased costs (in terms of increased maintenance efforts, increased degradation of bound capital, and train delays). The failure mode of one subsystem can inflict damage primarily to another subsystem and secondarily to itself. The root causes of problems are not always easy to assess. A dewirement could be the result of a damaged carbon slipper. The damage to the carbon slipper could be due to regular wear and tear and insufficient carbon slipper maintenance. It could also be caused by an obstructed pantograph motion path, inadequate contact wire alignment, hoarfrost, or too high a lift pressure of the pantograph, etc. (see causal maps in Figs 3 and 6). This line of reasoning illustrates the fact that the issue of controlling the degradation behaviour in the interface cannot be solved only by trying to prevent one of the identified failure modes. It is also important to be aware of the fact that applying a solution to gain control of one failure mode is not sufficient to gain control of the failure interaction effects within the system. Hence, a variety of different condition monitoring methods (manual or technological) must be applied in order to gain acceptable control of the critical failure modes that affect system degradation.

During the interviews, it was made clear that there is no effective quality assessment being made of the maintenance work performed on the infrastructure. STRIX makes it run and a failure report is sent to the maintenance contractor. However, once the maintenance work has been performed, there is no assessment or additional run made to verify the quality of the work performed. The same kind of problem can be identified with track tamping. To obtain a quality assessment of the work performed, more frequent measurements are needed.

In order to improve punctuality on the railways, one must acknowledge the symbiosis between the stakeholders. The functioning of the railway system depends on both the operators and the contractors taking their responsibility to deliver correct technical subsystem functions. Further, the operators and contractors depend on Banverket controlling all the actors and penalizing those who prevent other actors from delivering correct technical subsystem functions. Take, for example, an infrastructure maintenance contractor who does not perform adequate maintenance to prevent the presence of failure modes. This contractor can cause increased degradation and damage to all the operators' rolling stock (operational on the contractor's infrastructure). The affected operators will then run with damaged rolling stock on other contractors' track sections. Thus, the imposed degradation on the rolling stock can cause the infrastructure systems of other contractors to fail. This in turn can lead to increased maintenance efforts and costs.

Due to these failure interactions, Banverket needs information to monitor whether all the actors are performing as they should. This line of reasoning can be used to justify, for example, the necessity of equipping all the rolling stock with RFID tags to link deviating performance characteristics with the responsible parties.

It is important to consider the type of information that Banverket needs to assess the operators' and contractors' progress in ensuring proper railway system functions. Many interviewees felt that the bad actors (those who cause faults) must be penalized, since this seems to be the only way to make them perform better. However, due to the complexity of identifying what the initial failure was, and who caused it, the author suggests using condition monitoring technologies to identify and penalize the bad actors (operators or contractors) when failure occurs, rather than responding to faults. Or preferably, reward those who perform a better job than others, and in such a way make it beneficial for contractors and operators to excel in their maintenance practices.

It is interesting to reflect on the different roles of the stakeholders and their need for information on different levels. Banverket, the operators, and the maintenance contractors depend on the identified subsystem functions being under control to keep track of the degradation of the system, enabling the system to provide adequate service.

- Banverket primarily needs the information necessary to assess whether the operators and contractors are performing adequately to prevent the occurrence of failure modes. This information is rather primitive, stating either that they are acting properly or that they are not.
- The operators and contractors need the information necessary to assess the degradation of their respective systems, in order to assess when and where maintenance is to be performed to prevent failure modes.
- Banverket secondarily needs the information necessary to obtain adequate decision support for future modifications and reconstructions of the infrastructure system. It is essential that the input data should be within acceptable statistical control. This means that the statistics should be based on what caused the failure rather than what caused the final fault. In relation to this, the condition monitoring methods discussed can provide valuable input data for identifying the failures which, when correlated to rectification reports (cause of failure), can be used to identify weak links in the system (provided that the other failure modes are under control).
- Banverket also needs the information necessary to generate decision support for their process of constructing regulations or constructing contracts with economic incentives. With such information,

Banverket can assess how it can obtain value for money (how much functionality it can obtain per invested monetary unit). This information is valuable for adjusting rewards or penalties. If certain types of rolling stock systematically behave in undesirable ways, regulations for prohibiting them can be introduced.

The above discussion illustrates different applications of condition monitoring information. It is interesting to observe that, in all four cases, it is the same condition information that serves as input. The only difference is in the detail level. Even though the information may serve other application areas, this indicates the importance of having Banverket as the primary owner of the information and the monitoring systems, since the agency has a long-term commitment to assuring the functioning of the system. However, sharing information is equally important; i.e. it is equally important that the maintenance contractors and operators should be provided with the information so that they can provide the required subsystem functions.

5 DISCUSSION

It is difficult to generate delay statistics that represent the true causes of faults instead of the symptoms that are identified as the causes of faults. Therefore, to enable effective improvement efforts (e.g. redesign or acquisition of better material) based on statistics, there is a need for better correlation to the cause of the failure rather than the cause of the fault. Not knowing what the initial failure was that caused a fault is what causes difficulty when trying to estimate the improvement potential of applying condition monitoring solutions. What can be estimated from this study, however, is the improvement potential if all the identified failure modes are under control. Considering the figures presented in Fig. 2 and assembling all the causes, which correspond to the identified failure modes (pantograph failure, fatigue of material, unexpected mechanical stress, train vehicle, etc.), an estimated improvement of somewhere ∼60 per cent can be achieved.

Luminous arcs and sparks cause electromagnetic disturbances. A possible synergy effect of gaining control of the identified failure modes is that the electrical environment surrounding the railway might benefit from improved power conduction. Hence, NFF effects induced by electrical disturbance on adjacent wayside systems are likely to decrease as a result.

This is a first attempt to obtain a holistic perspective on the engineering interaction between Banverket's infrastructure and the operators' rolling stock. This study may therefore not have covered all the aspects of the problem formulation. One aspect that has not been considered is the malfunctioning of the locomotive's suspension, which may cause the train to tilt and thus position the pantograph incorrectly in relation to the contact wire. However, if all the other failure modes are under control, degradation of the pantograph's aluminium profile can indicate a problem (as long as it is not so severe as to cause a dewirement).

6 CONCLUDING REMARKS

It is apparent from this study that the current condition monitoring practices are not able to satisfy the need for information to control the failure modes within the system. Some of the applied condition monitoring methods are able to provide adequate information, but they are far from able to satisfy the need fully.

A system perspective is essential for determining what information is required to enable control of the failure modes within the system. The stakeholder perspective is essential for determining what to do with the information. From the study, it can be seen that the same kind of information can help the stakeholders to cope with their different responsibilities in different ways. Therefore, the stakeholder perspective adds an important dimension to the condition monitoring acquisition process; i.e. the process of acquiring technologies to serve the system and provide stakeholders with information that can form the basis of the decision support needed to perform effective and efficient maintenance management, and thus improve punctuality through more effective and efficient condition-based maintenance.

The methodology used was perceived by the participants to be structured and informative, as it helps to highlight the stakeholders' inter-relationships, responsibilities, and mutual dependence, as well as the engineering aspect of their respective subsystems' interaction. The methodology used seems applicable to systems dependent on the interactions between stakeholders and their respective subsystems, and can therefore be recommended for further use.

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